USGS Earthquake Hazards Program, Final Technical Report:

Bay Area Ground-Motion Site Effects: Exploring Site Spectral Physical Parameters: Collaborative Research with the University of Oregon and USGS

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Valerie J. Sahakian
Assistant Professor, Department of Earth Sciences
325D Cascade Hall
1272 University of Oregon
Eugene, OR 97403-1272
vjs@uoregon.edu, (541) 346-3401

Abstract

Ground-motion estimation is a fundamental component in determining seismic hazard. Local geology plays a role in the likely shaking at a given location, and can be determined a priori. One such parameter is κ, or the attenuation of high-frequency energy at a site. Included in more stochastic and more recently empirical ground-motion models (GMMs), (Laurendeau, et al. 2013, Boore 2003), κ has been shown to correlate with intensity measures of high-frequency ground-motion (Silva and Darragh 1995, V. J. Sahakian, et al. 2018). It is however, an entirely empirical parameter, and its connections to local geology and physical mechanisms remain unknown. As such, it is only possible to compute in regions of high seismicity. There are currently no values of κ at seismic stations in the San Francisco Bay Area. This work computes values of κ in this region, and aims to produce spatially-varying maps of κ for use in non-ergodic ground-motion models.

Introduction

A variety of parameters exist to describe the amplification (or lack thereof) at a site, at various frequencies. These include V_{S30}, or the average shear-wave velocity in the top 30 meters of the crust; f_d, or dominant frequency of amplification at a site, often due to resonance or basin effects; and κ, a measure of the high-frequency S-wave spectral decay of a seismic recording (Anderson and Hough 1984). V_{S30} is useful in that it can be both measured, as well as inferred from terrain- and geology-based proxies, which can provide an estimate virtually anywhere globally. However, it is often not representative of site effects, in particular when using a proxy value (V. J. Sahakian, et al. 2018, Yong, et al. 2012). The dominant site frequency (f_d) describes well the amplification present at a specific frequency, but the absolute value of amplification is sometimes not well-known, and may not represent relative amplification or de-amplification of the full spectrum (Field and Jacob 1995).

Κ describes the high-frequency decay of energy at a station, past the corner frequency and fmax (Hanks,1982). Its determination requires measuring this decay on a large number of reliable seismic records, producing a single value of κ at each seismic station – or a discrete measurement in space. In the past decade, this parameter has become useful in empirical GMMs, and found to correlate with observed high-frequency intensity measures (5 – 10 Hz), and peak ground acceleration (PGA). Higher values of κ correlate with lower peak ground-motions, implying that low levels of attenuation of high-frequency energy promote higher ground-motions at a site (Silva and Darragh 1995, C. van Houtte, et al. 2014, Klimasewski, et al. 2019). Similar to VS30, κ is related to local site geology and conditions. However, it likely also represents the effects of a larger volume around the site. As such, more recent GMMs have begun to include κ as a predictor variable (Laurendeau, et al. 2013). Because κ is an empirical parameter, computed from many seismic records at a station, relationships with Vs30 are also of interest, for corrections in GMMs.

Unlike Vs30, κ has a defined mathematical influence on ground-motion amplitudes, making it a valuable parameter in stochastic and semi-stochastic ground-motion estimation, as well as physics-based ground-motion simulations (Motazedian and Atkinson 2005, Graves and Pitarka 2010, Mai and Dalguer 2012). Furthermore, although κ is a discrete parameter that can only be measured at a seismic station, there are spatially varying models of κ, such as those produced for New Zealand by (C. van Houtte, et al. 2017). These are useful in that they provide continuous spatial coverage of a physics-based site parameter for high-frequencies, with an associated uncertainty. The engineering community is moving towards fully non-ergodic ground-motion models – ground-motion models in which the relationships between source, path, and site parameters are specific to individual paths. To accomplish this, future site parameters should be spatially-varying as well – and such κ models will accomplish this (Landwehr, et al. 2016, V. J. Sahakian, et al. 2019).

Values of κ do not exist in the greater San Francisco Bay Area/Northern California region. Although studies of site amplification here are numerous (and in fact, host some of the first studies of relationships between local geology and ground-motions, (Borcherdt 1970)), these works focus mainly on Vs30 and dominant site frequency. The area hosts high seismicity, and boasts broad seismic networks, both conducive to determining values of κ. Our work proposed to compute κ at existing broadband and strong-motion stations in the San Francisco Bay Area. Furthermore, we proposed to compare these values to observed ground-motion site residuals compared to a regional GMM, and produce a spatially-varying map of κ following the method of (C. van Houtte, et al. 2017).

The uses of obtaining both discrete and continuous values of κ in the region include characterizing high-frequency site effects via empirical ground-motion models, having ground-truthed values to implement in stochastic simulations, as well as to improve the high-frequency prediction of physics-based numerical simulation efforts in the region, such as the work of (Rodgers, et al. 2020).

Computing Κ

Anderson and Hough (1984) defined κ as a measure of the high-frequency S-wave spectral decay of a seismic recording:

$$A(f\ ) \ = \ A_0 e^{-\pi f \kappa} \tag{1}$$

where $a(f\ )$ is the amplitude of the acceleration spectra at any frequency, f, and $A0$ is a constant. In this original study, κ was not distinguished as being solely a site effect, and in fact is mathematically very similar to $t*$ (a parameter required to compute Q, or seismic quality factor, more typically considered a property of the path). In this formulation, they found a correlation between their observed values of κ per recording, and the distance between source and station of that recording. They (and, subsequently (Hough, et al. 1988)) therefore suggested a linear relation between distance, and κ:

$$\kappa = \kappa_0 + \kappa(R) \tag{2}$$

where κ_0, the intercept of this linear trend, is a parameter of the site, and κ_R is the source- to-site distance. Since then, many others have modeled κ, and in various ways, including simultaneously solving for the corner frequency of the source.

In our original project, we proposed to use a modified generalized inversion approach to first solve for the individual site and event spectra, and subsequently obtain κ and other spectral levels from the site spectra, per seismic station. This relied first on the (Andrews 1986) inversion method to solve for event and site spectral amplitudes in various frequency bands:

$$\ln\, R_{ij}(f) = \ln E_i(f) + \ln S_j(f) \tag{3}$$

where $R_{ij}(f)$ is the record spectra for event I and station j at frequency f, and $E_i(f)$ and $S_j(f)$ are the event and site spectra, respectively. A degree of freedom remains from this inversion, thereby producing event and site spectra that are only relative to each other, as opposed to constrained to an absolute amplitude. Andrews (1986) constrained this by choosing a reference site by which to divide and multiply all spectra, respectively; but this method renders the reference site unusable for site studies. As such, we proposed to use the new method of Klimasewski et al. (2019), which determines a constraint function as the deviation of a “model” event in the catalog from its theoretical Brune spectrum. This “model” event has a shape very similar to a Brune spectrum, which produces a constraint function of a nearly constant value at all frequencies, thereby shifting all events and sites to higher or lower amplitudes without changing their shape. This method worked very well in Southern California, wherein Klimasewski et al. (2019) computed κ values via this spectral decomposition approach and found them to be very similar to that of Anderson & Hough (1988), as well as other workers.

In comparison to other methods of computing κ, this approach inverts for the site spectra as opposed to only the parameters describing the site and source (like κ, and corner frequency). The benefit of this is that we may use the spectra to obtain other parameters of the site in addition to κ.

Dataset

We collect seismic records from 260 earthquakes, at 24 broadband and 261 strong-motion stations in the San Francisco Bay area, recorded between 2000 and 2018. All events are >**M**3.5, and were recorded at stations <250km epicentral distance. Most events are 3.5 < **M** < 4, the largest being **M**5.5. Following the recommendations of Ktenidou et al. (2013), we cull our dataset by requiring that records have a signal-to-noise ratio (SNR) of at least 5.

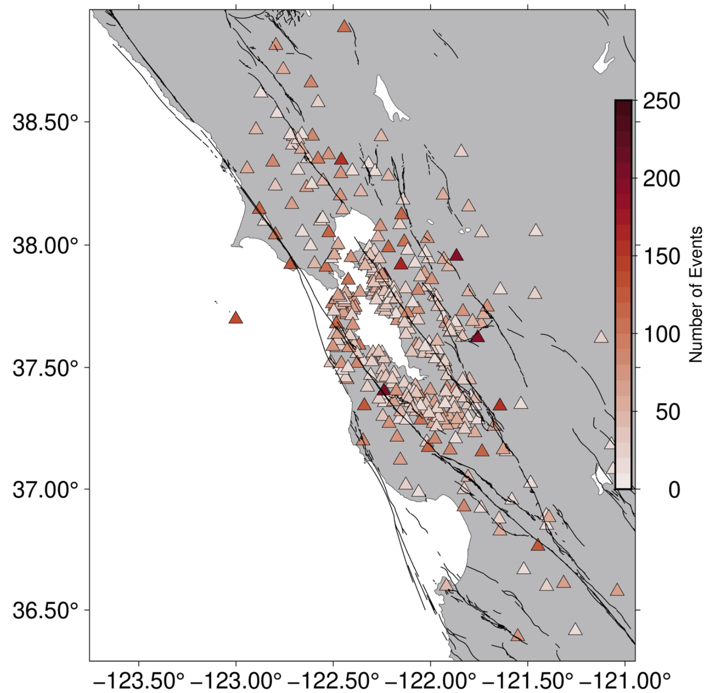

Figure 2 - Regional map with all stations, colored by the number of events they record.

Methods

In solving for each record's κ, we modify the approach of Klimasewski et al. (2019), and use an algorithm to determine the frequency ranges in which to solve for κ. Following a method more similar to Ktenidou et al. (2013), we solve between a minimum frequency, f_e, which must be larger than f_{max}, and a maximum frequency, f_x.

To do so, we first fit a polynomial of the 10[th] degree to each spectra, to create a smoothed spectra. We chose 10 degrees as this demonstrated the best misfit overall for the dataset. We take f_e as the larger of: (1) the minima of the polynomial's first derivative (the location of steepest descent, which occurs after fmax), or (2) the predicted corner frequency of the event assuming a stress drop of 5 MPa, to ensure that no source effects contaminate the results. Many spectra decay until a frequency and then plateau, as opposed to decaying constantly until the maximum observable frequency (35 Hz, 5 Hz lower than the Nyquist frequency of the lowest sampling rate in the dataset). To find the maximum frequency, we compute the second derivative of the spectra's polynomial fit, and take f_x to be the location of

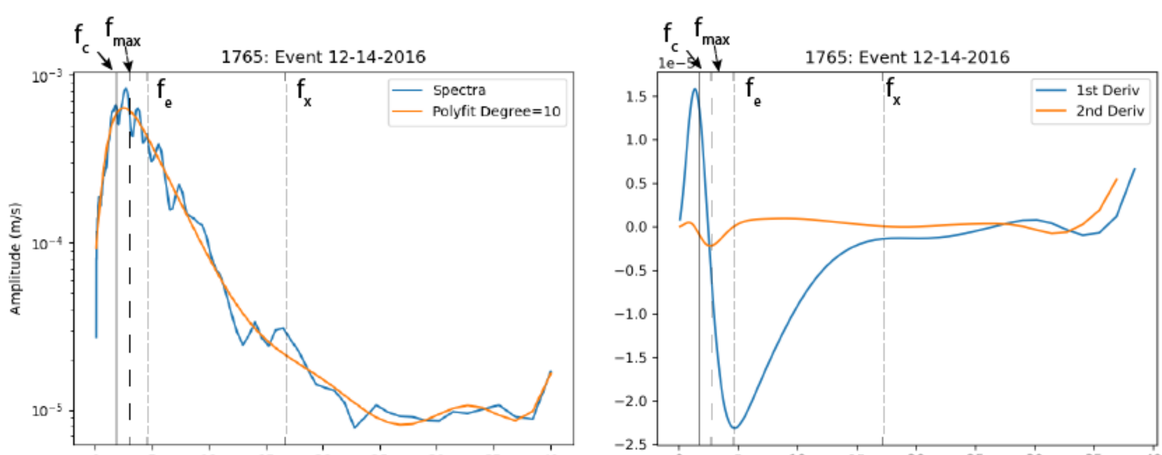

Figure 1 - Example spectra and polynomial fit (left), with interpreted corner frequency (f_c) and fmax, as well as computed f_e and f_x. Right: First and second derivatives of the polynomial, with interpreted fc and fmax, as well as f_e and f_x determined from the algorithm.

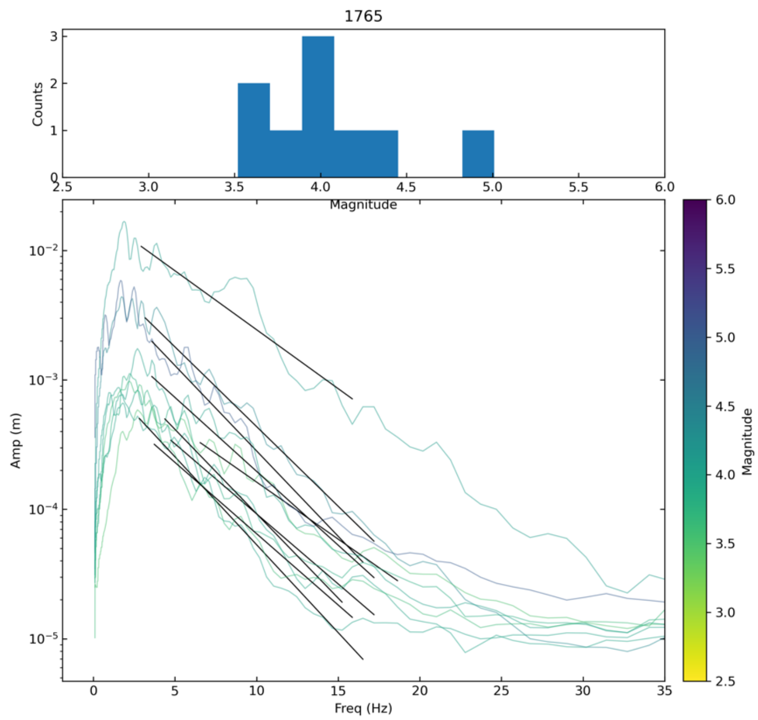

Figure 3 - Example plot of all spectra at station 1765 with a histogram of their magnitudes, and the resulting fits for κ between each record's fe and f_x (black lines).

the first zero-crossing after f_e. Thus, f_e and f_x are unique for each spectra, providing us with the most robust estimate of κ per record.

To compute κ0, we perform a weighted least-squares regression on all values for a given station, weighted by the standard deviation of each κ record. This provides us with a value of κ0, as well as an associated uncertainty, for every station.

Results

As proposed, we first computed κ at broadband and strong-motion stations in our dataset via the spectral decomposition approach of Klimasewski et al. (2019). Many values are unreasonably high, suggestive of a strong path attenuation component retained in the site spectra. Additionally, the spectral shapes of many event and site spectra are very unlike what is expected for a theoretical Brune spectrum. Unlike Southern California, the raypaths in the San Francisco Bay area are much more biased towards sampling single-azimuth and similar paths. In Southern California, the ANZA network is centrally located between fault structures, allowing for a more heterogeneous sampling of the paths' crust. We find that this bias creates a challenge for the spectral decomposition approach of Klimasewski et al. (2019), which assumes all stations are independent and does not include a path component.

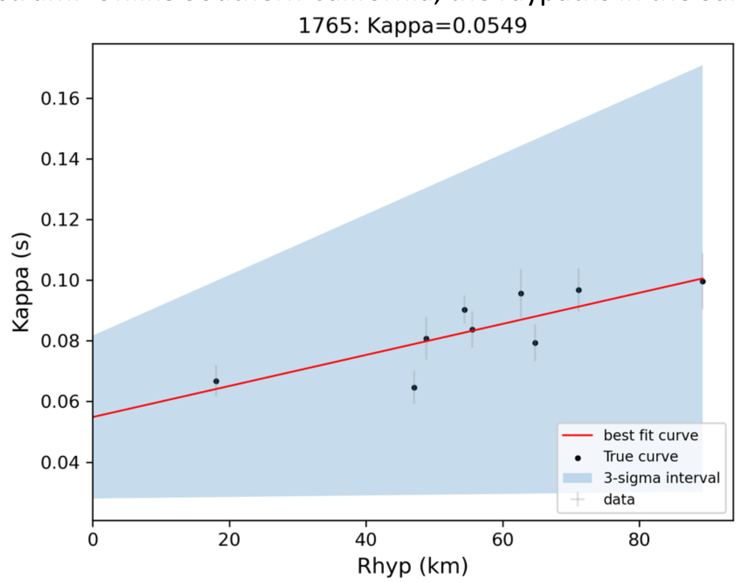

Figure 4 - K values as a function of distance for the same site as Figure 3, 1765. The red line shows the best fit line, with the blue region demonstrating the 3 standard deviation uncertainty from the weighted regression. This site's κ is computed as the red line.

We thus applied the traditional method, outlined in Anderson & Hough (1984), as well as (Ktenidou, Gélis and Bonilla 2013). Using the same record spectra, we computed κ on the acceleration spectra of each record, and subsequently determined κ0 from the y-intercept of all κ values at a given station, as a function of distance. We retained the uncertainty inherent in the spectral decomposition approach (Klimasewski, et al. 2019), propagating each individual record's uncertainty through to the station κ via a weighted regression.

This method is much more robust in the region. The resulting κ values are more realistic given the local geology, the inter-station variability is improved, and it also allows for greater flexibility in the computation of κ via dataset selection (distance, magnitude, etc.). Lastly, this method follows the protocol outlined in Ktenidou et al. (2013), which is a more accepted method of determining κ. The downside is that this method does not allow us to compute spectral levels, yielding a single site parameter (κ).

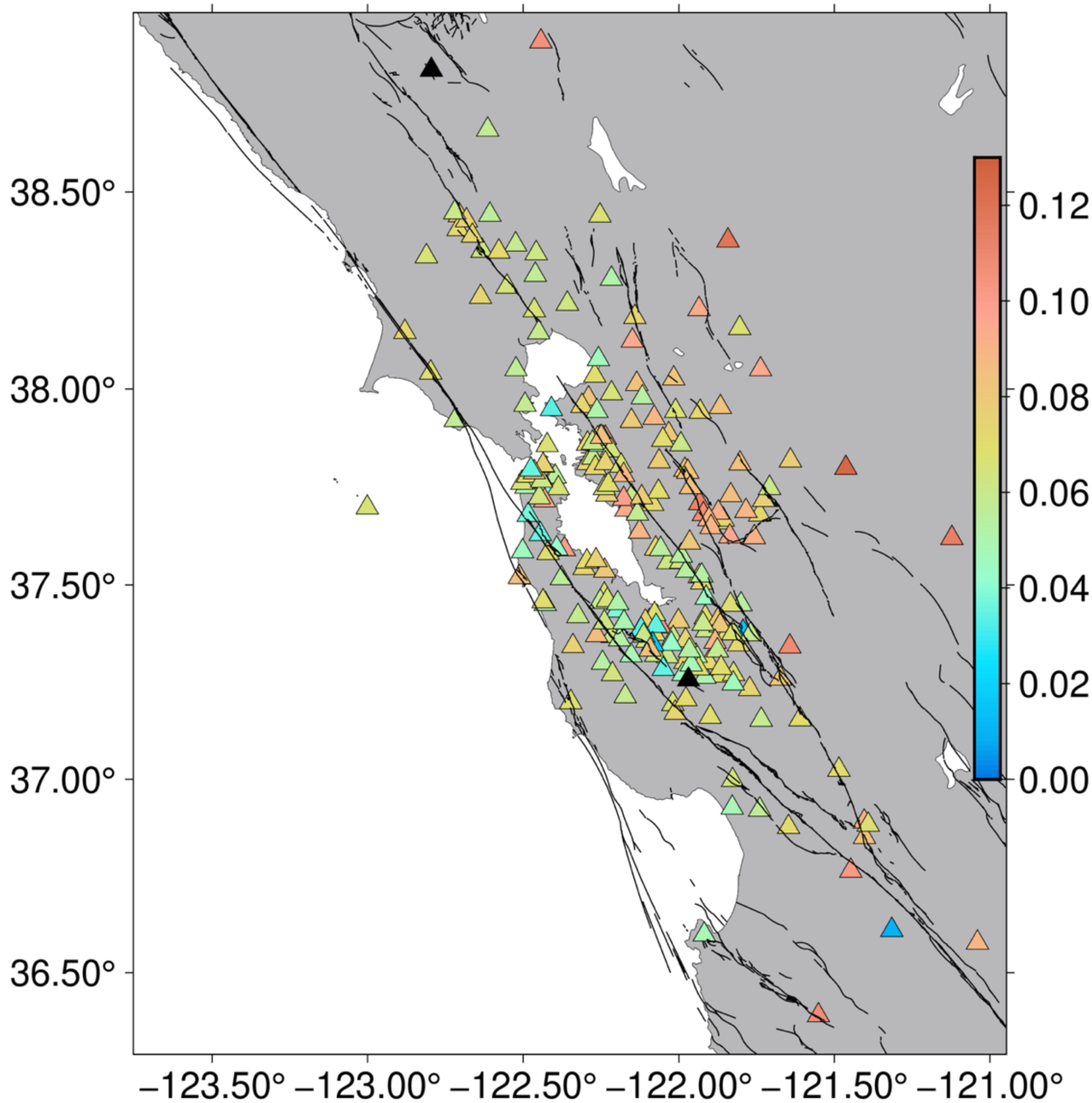

Figure 5 - Resulting κ values for the region.

We find some of the highest values of κ in the San Joaquin River Delta, to be expected due to the thick mantle of deltaic sediments (Figure 5). Regions of hard rock correlate to the lowest κ values, in line with existing interpretations (Figure 6). Near the Rodgers Creek fault, we find moderate values of κ, correlating to regions of low PGA residuals seen in the Napa earthquake (Baltay and Boatwright 2015). In other words, regions that have demonstrated lower high-frequency ground-motions than expected in past earthquakes seem to correlate with moderate κ values, or increased attenuation of high-frequencies.

Lastly, our model demonstrates a high degree of spatial dependence between stations, despite the fact that this method does not assume dependence. This suggests to us that these values are robust, and honor regional geologic or structural patterns in the subsurface, and indicate that this may play a strong role in high-frequency site effects.

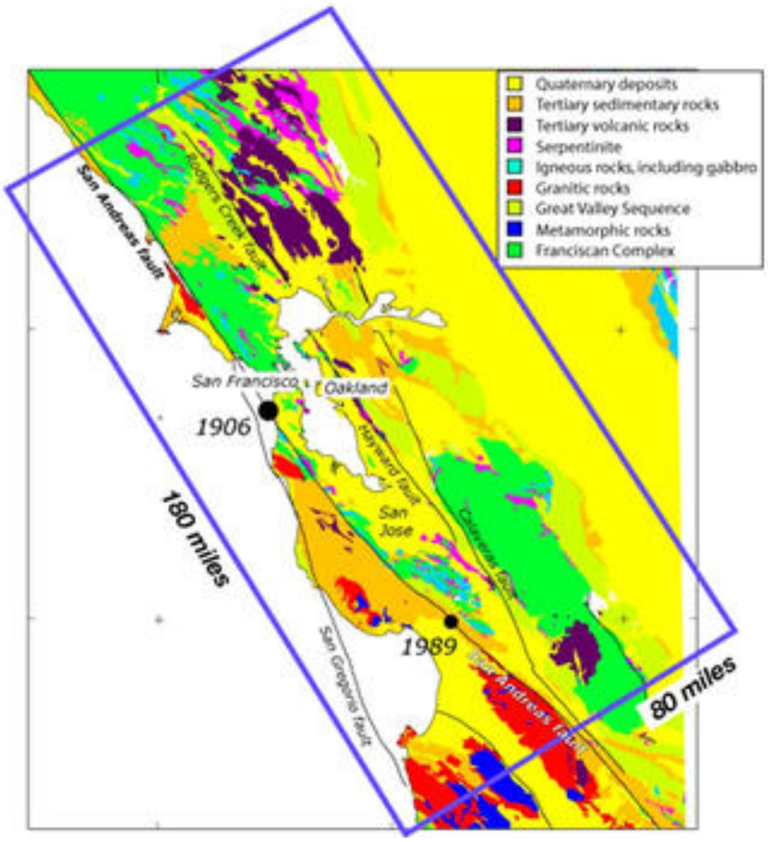

Figure 6 - Regional geologic map from Bay Area seismic velocity model.

Correlations between κ and empirical site terms from GMMs are forthcoming. We have computed observed intensity measures of PGA and PGV in our record dataset. Using the (Abrahamson, Silva and Kamai 2014) GMM (which extends to **M**3.5 as does our dataset), we have computed predicted values of PGA and PGV for every record. We will apply the mixed-effects residual decomposition approach in Sahakian et al. (2018) to determine site-specific GMM residuals for every station in our dataset, and subsequently compare these to the observed κ values. Finally, we are computing a spatially-variable map of κ for a final publication, using the kriging approach of van Houtte et al. (2017). This will yield both a regional map of continuous κ values, as well as a complementary map of associated uncertainties, given the uncertainties in individual station κ values, as well as the kriging process.

Conclusions

We have computed values of κ at 285 broadband and strong-motion seismic stations in the greater San Francisco Bay Area. Using two methods, we have determined that the traditional approach of computing κ excels here, and is superior to the spectral decomposition approach of

Klimasewski et al. (2019). We find high values of κ in the San Joaquin River Delta, low values in areas of hard rock, and general correlation ith existing observations of high or low ground-motions in the 2014 Napa earthquake. We also find a high degree of spatial dependence, despite no such assumptions in the computation method. Relationships between κ and site-specific ground-motions, as well as a spatially-variable map will be present in a forthcoming publication.

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Project Data

A publication containing this work, as well as the associated products to be disseminated publicly (κ values, κ map) is forthcoming, in preparation (see below). Its planned submission is November 2021.

Project Publications

T. Nye, V.J. Sahakian, E. King, A. Baltay (in prep). "Estimates of K in the San Francisco Bay Area", Bull. *Seis. Soc. Of Am.*

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